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ORIGINAL ARTICLE

The energetics of ultra-endurance running

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Abstract Our objective was to determine the effects of long-lasting endurance events on the energy cost of running (C_r), and the role of maximal oxygen uptake (VO_{2max}), its fractional utilisation (F) and C_r in determining the performance. Ten healthy runners (age range 26–59 years) participated in an ultra-endurance competition consisting of three running laps of 22, 48 and 20 km on three consecutive days in the North–East of Italy. Anthropometric characteristics and VO_{2max} by a graded exercise test on a treadmill were determined 5 days before and 5 days after the competition. In addition, C_r was determined on a treadmill before and after each running lap. Heart rate (HR) was recorded throughout the three laps. Results revealed that mean C_r of the individual laps did not increase significantly with lap number ($P = 0.200$), thus ruling out any chronic lap effect. Even so, however, at the end of lap 3, C_r was 18.0% ($P < 0.001$) greater than before lap 1. In addition, a statistically significant acute lap effect on C_r was observed at the end of the second and third laps (by 11.4 and 7.2%, respectively). The main factors determining performance were VO_{2max}, F, as estimated from the average HR, and the average $C_{r\text{-mean}}$ throughout the three laps; the grand average speed over the three laps being described by $v_{\text{end-mean}} = F \times VO_{2max} \times C_{r\text{-mean}}^{-1}$. We concluded that (1) the substantial increase of $C_{r\text{-mean}}$ during the competition yields to marked worsening of the performance, and (2) the three variables F, VO_{2max} and $C_{r\text{-mean}}$ combined as described above explaining 87% of the total competition time variance.

Keywords Maximal oxygen uptake · Energy cost · Ultramarathon · Gas exchange threshold · Efficiency

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Introduction

The energy cost of running (C_r) is generally expressed as the amount of energy spent above resting to transport 1 kg body mass over 1 m distance. As such it is obtained by dividing the steady-state oxygen uptake (VO_2), above the value measured at rest in standing position, by the running speed. To express C_r into energy, the respiratory quotient (RQ) should be known. However, since the energy equivalent of O_2 varies only from 21.13 to 19.62 kJ/l (from pure glycogen to pure fat oxidation), it is convenient to stick to one single value; often 20.9 kJ/l, which corresponds to an RQ of 0.96, a reasonable value for aerobic exercise below gas exchange threshold. For simplicity, throughout this study we will express (C_r) in the most familiar O_2 units ($mlO_2\ kg^{-1}\ m^{-1}$).

C_r is independent of the speed, at least for speeds from 2.2 m s^{-1} (8 km h^{-1}) to about 5 m s^{-1} (18 km h^{-1}) wherein the air resistance is negligible in which cases the fraction of C_r due to the air resistance is ≤5% of the total (Jones and Doust 1996). When normalized per unit of body mass, C_r above resting, on flat compact terrain, shows a 10–20% variability among subjects: the average value reported by di Prampero et al. (1986) amounting to 0.182 ± 0.014 mlO$_2$ kg^{-1} m^{-1} (3.80 ± 0.29 J kg^{-1} m^{-1}). Trained long-distance runners are characterised by lower C_r than less trained ones, even though the role of long-term training and of natural endowment are difficult to disentangle (Beneke and Hutler 2005).

The variability of C_r among subjects is relatively minor, nevertheless C_r is crucial in determining the best performance times over distances between 800 m and the marathon, together with maximal O_2 consumption (VO_{2max}), the fraction (F) of it that can be sustained throughout the competition, and the maximal capacity of the anaerobic stores (di Prampero et al. 1986, 1993). Indeed, consider two runners, whose physiologic characteristics are exactly the same, with one exception: the C_r of runner A is 5% less than that of runner B, a difference well within the expected variability. If this is so, and since the speed of running is determined by the ratio between metabolic power and energy cost (see Eq. 1), the velocity of runner A will be systematically 5% larger (and hence the running time 5% shorter) than that of runner B, a colossal difference when dealing with top athletes' performances.

A typical example thereof was reported by Jones (1998) who, over a 5-year period, observed an 8% increase in the 3,000 m running speed of an Olympic runner, whereas over the same period VO_{2max} decreased by 10%. The fall of VO_{2max} was compensated by a decrement of C_r: indeed, during treadmill running at a slope of 1%, it decreased from 0.200 to 0.180 mlO$_2$ kg^{-1} m^{-1}. Furthermore, the performance improvement was also linked to an increase of the lactate threshold from 80 to 88% VO_{2max}, thus suggesting an increase of the fraction of VO_{2max} sustainable throughout the effort.

In spite of the crucial role of C_r in running performance, only a few studies have been devoted to assess the effect of fatigue, (e.g., during endurance running) on it. Davies and Thompson (1986), during 4 h treadmill running at constant speed observed a linear increase of VO_2 with time from the 50th to 240th min, the rise becoming significant ($P < 0.01$) after 110 min of work. Brueckner et al. (1991) observed a significant increase in C_r (of about 0.142% per km of distance) during a marathon competition, the increase being particularly evident in some runners. In addition, Millet et al. (2009) observed a significant increases in C_r (+6.2%) 3 weeks after the end of the ultra endurance running performance from Paris to Beijin (8,500 km in 161 days), associated with, and probably due to, changes in the biomechanics of running.

To further investigate the effects of long-lasting endurance running on C_r, as well as on the factors determining performance in this type of activity, we evaluated a group of amateur runners participating in a 90 km trail run in three laps named "Magraid". To this aim, we assessed VO_{2max} 5 days before and 5 days after the competition, the fraction of it maintained throughout each lap (F), as estimated from heart rate (HR) recordings, as well as C_r, before and immediately after each lap.

Research design and methods

Subjects

Twelve healthy Italian male amateur runners (age range 26–59 years) were enroled in June 2009 as participants to the ultra-endurance competition designed "Magraid". The experimental protocol was approved by the Ethics Committee of the University of Udine. Before the study began, the purpose and objectives were carefully explained to each subject and written informed consent was obtained from all subjects. Subjects having any overt metabolic and/or endocrine diseases and those taking medications regularly or using any drugs known to influence energy metabolism were excluded. The participants completed questionnaires on physical exercise activity, demographics, medical history, alimentary habits, and lifestyle (Craig et al. 2003). Of the 12 subjects eligible for the study, only 10 completed the entire competition. Therefore, the final data analysis was performed on these 10 male runners only. Training load and number of competitions (endurance events) in the year preceding this study, as evaluated by means of the questionnaire mentioned above (Craig et al. 2003), amounted to 6.6 ± 2.7 h week^{-1} (from 3 to 12 h week^{-1}) and to 4.4 ± 5.1 endurance events (from 3 to 18), respectively.

Study protocol

The competition, named "Magraid", took place in June 2009; it consisted of three running laps of 22, 48 and 20 km on three consecutive days in the North–East of Italy. The geologic texture of the terrain is an unusual soil in respect the vast majority of ultra-endurance competitions, it is characterised by a gravel (locally named "Magredi") from the braided river "Cellina-Meduna". The first day, the Lap 1 began at 6.00 p.m. with temperature and relative humidity of 31°C and 41%. The second and third days, the Laps 2 and 3 began at 10.00 a.m. with temperature and relative humidity of 17 and 18°C and 76 and 69%, respectively.

Anthropometric characteristics, body composition, VO_{2max}, maximal heart rate (HR_{max}), and C_r were measured 5 days before and 5 days after the race. In addition, C_r, respiratory exchange ratio (RER) and body mass were determined before and immediately after each running lap, and HR was continuously recorded throughout the three laps.

Anthropometric characteristics and body composition

Body mass (BM) was measured to the nearest 0.1 kg with a manual weighing scale (Seca 709, Hamburg, Germany) with the subject dressed only in light underwear and no shoes. Stature was measured to the nearest 0.5 cm on a standardised wall-mounted height board. Body mass index (BMI) was calculated as BM (kg) stature^{-2} (m).

Body composition was measured by bioelectrical impedance (BIA, Human IM Plus; DS Dietosystem, Milan, Italy). In order to the reduce measurement faults, data were collected according to the method of Lukaski et al. (1986) after an overnight fast and after 20 min rest in a supine position with relaxed arms and legs without any contact with other body parts. Body composition (fat-free mass, FFM, and fat mass, FM) was obtained from the software provided by the manufacturer.

Physiological characteristics

VO_{2max} and HR_{max} were determined by a graded exercise test on a treadmill (Saturn, HP Cosmos, Germany) under medical supervision. During the experiment, ventilatory and gas exchange responses were measured continuously with a metabolic unit (Quark-b^2, Cosmed, Italy). The volume and gas analysers were calibrated using a 3-L calibration syringe and calibration gas (16.00% O_2; 4.00% CO_2), respectively. During the tests, electrocardiogram was continuously recorded and displayed on line for visual monitoring, and HR was measured with a dedicated device (Polar, Finland). Before the start of the study, subjects were familiarised with the equipment and the procedures.

The tests were always performed 5 days before and 5 days after the race and comprised a 5-min rest period followed by running at 10 km h^{-1} for 5 min (at a slope of 1%); the speed was then increased by 0.7 km h^{-1} every minutes until volitional exhaustion. A levelling off of oxygen uptake (defined as an increase of no more than 2 ml kg^{-1} min^{-1}) was observed in all subjects during the last 1 or 2 min of the exercise test indicating the VO_{2max} had been attained. VO_{2max} and HR_{max} were calculated as the average oxygen uptake and HR of the last 30 s of the test. RER was calculated as $VCO_2 \times VO_2^{-1}$. The gas exchange threshold (GET) was determined by the V-slope method (Beaver et al. 1986).

The C_r (mlO$_2$ kg^{-1} m^{-1}) was determined before the incremental tests when the subjects ran on a treadmill at 10 km h^{-1} for 5 min, dividing the net (above resting) steady-state VO_2 observed over the fifth minute by the speed.

In addition, C_r and RER were determined on a treadmill before and immediately after each running lap, positioned near the arrival line, where the athletes ran for 5–7 min at a constant speed of 10 km h^{-1} and HR was continuously recorded throughout each lap, by means of a portable device (Polar, Finland). Finally, as mentioned above, a questionnaire about usual physical activity and sports performed was completed by each subject (Craig et al. 2003).

Statistical analyses

Statistical analyses were performed using PASW Statistic 18 (SPSS Inc., IL, USA) with significance set at $P < 0.05$. All results were expressed as mean values and standard deviation (SD).

Five days before and five days after the race, anthropometric characteristics, body composition and physiological characteristics were compared by means of paired t test.

The chronic lap effect (called "Lap": lap 1 vs. lap 2 vs. lap 3) and the acute lap effect (called "Time": before vs. after) on C_r, RER and BM were studied with GLM Repeated Measures with two factors. When significant differences were found, a Bonferroni post hoc test was used to determine the exact location of the difference.

The role of each factor (VO_{2max}, F, and C_r, see above) presumed to affect performance was evaluated as follows. Simple linear regressions were first determined between each variable and performance time. Subsequently, the variables which met a statistical significance level ($P \leq 0.05$) were retained. Finally, a multiple linear regression analysis among these variables and performance time was performed. This multivariate analysis enabled us to assess the influence of each variable on the athletes' performance.

Results

Physiological characteristics of subjects

The anthropometric and physiological characteristics of the 10 subjects (mean age 38.2 ± 12.4 years) who completed the race, as determined 5 days before and 5 days after the competition, are reported in Table 1. Five days after the race, BM, FFM and FM were essentially unchanged; VO_{2max} and C_r tended to decrease by about 9% ($P > 0.05$). Whereas, HR_{max} and HR_{GET} decreased significantly by 3 and 7%, respectively ($P < 0.05$).

Physiological responses to the race

Running time, mean velocity and mean HR of the three laps are reported in Table 2. Mean cumulative running time was 9:25:50 ± 2:12:00 h, mean speed was 9.8 ± 2.1 km h^{-1} and mean $\%HR_{max}$ was 83 ± 4% (corresponding to 74 ± 7% of VO_{2max}). When considering the overall mean time of performance (9:25:50 h), it turns out that HR was maintained between 80 and 89% of its maximum for about 45% of the total race duration; it was lower than 69% and between 70 and 79% of HR_{max} for 15 and 20% of the total, respectively. Finally, HR was >90% HR_{max} for about 19% of the race duration.

Table 1 Anthropometric characteristics, body composition and physiological characteristics of subjects ($n = 10$), 5 days before and 5 days after the race

	Before	After	P
Age (years)	38.2 ± 12.4	–	
Stature (m)	1.76 ± 0.07	–	
Body mass (kg)	74.5 ± 7.3	74.6 ± 7.5	0.780
BMI (kg m^{-2})	24.1 ± 1.6	24.2 ± 1.6	0.534
FFM (kg)	62.3 ± 5.2	62.7 ± 5.5	0.087
FM (kg)	12.1 ± 4.0	11.9 ± 3.8	0.343
FM (%)	16.1 ± 4.8	15.7 ± 4.6	0.257
VO_{2max} (ml min^{-1})	4,018 ± 526	3,750 ± 409	0.101
VO_{2max} (mlO_2 kg^{-1} min^{-1})	54.1 ± 6.8	49.2 ± 3.9	0.124
HR_{max} (bpm)	170 ± 10	165 ± 9	0.009
v_{max} (km h^{-1})	16.3 ± 1.4	16.5 ± 1.8	0.095
VO_{2GET} (ml min^{-1})	3,387 ± 466	3,182 ± 375	0.186
VO_{2GET} (% of VO_{2max})	84 ± 2	85 ± 4	0.782
HR_{GET} (bpm)	154 ± 13	143 ± 10	0.018
HR_{GET} (% of HR_{max})	90 ± 3	87 ± 4	0.099
v_{GET} (km h^{-1})	13.4 ± 1.2	13.1 ± 1.6	1.000
v_{GET} (% of v_{max})	73 ± 26	79 ± 6	0.460
C_r (mlO_2 kg^{-1} m^{-1})	0.182 ± 0.021	0.165 ± 0.024	0.057

All values are mean ± standard deviation (SD)

BMI body mass index, *FFM* fat-free mass, *FM* fat mass, VO_2 oxygen uptake, *HR* heart rate, *v* velocity, *GET* Gas exchange threshold, C_r energy cost of running

P significance by paired *t* test

As shown in Table 3, the mean C_r of the individual laps did not increase significantly with lap number ($P = 0.200$), thus ruling out any chronic lap effect. Even so, however, at the end of lap 3, C_r was 18.0% ($P < 0.001$) greater than before lap 1. In addition, a statistically significant acute lap effect on C_r was observed at the end of the second and third laps (by 11.4 and 7.2%, respectively). Finally, the interaction (lap × time) was not significant. The mean value of RER calculated over the entire lap 2 was significantly lower than that determined over lap 1 ($P = 0.032$, Table 3). In addition, an acute lap effect on RER was detected only in lap 2 (−4.6%, $P = 0.013$) and lap 3 (−2.5%, $P = 0.048$). Finally, no chronic lap effect on BM was shown (Table 3). However, an acute lap effect on BM was observed after the first and second lap (by 1.9 ± 1.1 and 1.5 ± 0.7 kg ($P < 0.001$), respectively).

Discussion

The main results of the present study showed that: (1) C_r increased significantly at the end of the second and third laps, being about 18.0% higher at the end of lap 3 than before lap 1 and 2) the mean HR maintained during each of the three laps amounted to 88 ± 3, 79 ± 7, and 81 ± 7% of HR_{max}, respectively (see Table 2).

The average value of C_r determined before lap 1 is essentially equal to that obtained by other authors during treadmill running (0.182 mlO_2 kg^{-1} m^{-1}). The corresponding RER amounted to 0.85; therefore, assuming that in these conditions RER is equal to the metabolic respiratory quotient, and hence 1 mlO_2 ~20.3 J, C_r, expressed in terms per "true" energy expenditure amounted to 3.70 ± 0.45 J kg^{-1} m^{-1}. RER decrease slightly over each lap. Even so, the corresponding energy equivalent of O_2 was not substantially smaller than the value report above, attaining a minimum of 20.1 J ml^{-1} after lap 2. Therefore, the general trend of the changes of C_r over the three laps is not significantly affected when expressing C_r in actual energy expenditure (i.e. taking into account also the RQ), as compared to the raw data expressed in mlO_2.

Middle- and long-distance running performances depend on several physical, physiological, metabolic,

Table 2 Running time, mean velocity (v_{mean}) and mean heart rate (HR_{mean}) of the three laps ($n = 10$)

	Lap 1 (22 km)	Lap 2 (48 km)	Lap 3 (20 km)
Running time (hh:mm:ss)	1:58:29 ± 0:20:26	5:29:33 ± 1:24:39	1:57:48 ± 0:29:41
	[1:35:59; 2:42:25]	[3:55:18; 7:54:02]	[1:25:24; 2:54:41]
v_{mean} (km h^{-1})	11.8 ± 1.8	8.6 ± 2.0	10.4 ± 2.3
	[8.4; 14.2]	[5.7; 11.4]	[6.6; 13.6]
HR_{mean} (% of HR_{max})	88 ± 3	79 ± 7	81 ± 7
	[81; 91]	[67; 89]	[67; 92]

All values are mean ± standard deviation (SD). Range in square brackets

Table 3 The energy cost of running (C_r), respiratory exchange ratio (RER) and body mass (BM) determined before and immediately after each lap

	Lap 1 (22 km)		Lap 2 (48 km)		Lap 3 (20 km)		*P*		
	Before	After	Before	After	Before	After	Lap	Time	$L \times T$
C_r (mlO_2 kg^{-1} m^{-1})	0.182 ± 0.022 [0.154; 0.216]	0.194 ± 0.019 [0.172; 0.222]	0.183 ± 0.020 [0.160; 0.213]	0.204 ± 0.022 [0.168; 0.237]	0.193 ± 0.009 [0.184; 0.203]	0.207 ± 0.014 [0.185; 0.223]	0.200	0.001	0.355
RER	0.85 ± 0.03 [0.82; 0.92]	0.84 ± 0.04 [0.80; 0.91]	0.83 ± 0.04 [0.77; 0.90]	0.79 ± 0.04 [0.74; 0.87]	0.84 ± 0.05 [0.76; 0.89]	0.81 ± 0.02 [0.78; 0.84]	0.012	0.003	0.104
BM (kg)	75.0 ± 8.1 [60.5; 85.0]	73.1 ± 7.7 [58.0; 83.5]	74.1 ± 7.7 [60.0; 86.5]	72.6 ± 7.3 [59.0; 84.5]	73.5 ± 7.8 [59.0; 86.0]	73.4 ± 7.2 [59.5; 85.0]	0.200	0.001	0.001

All values are mean ± standard deviation (SD). Range in square brackets

Significance by GLM Repeated Measures with two factors of the main effects of Lap (*L*), Time (*T*, before vs. after) and interaction ($L \times T$)

psychological and social factors (di Prampero et al. 1986, 1993; Joyner 1991). In particular, crucial physiological characteristics for determining high level performance in long-distance running are: (1) a large value of VO_{2max}, (2) a large fraction (*F*) of VO_{2max} that can be sustained throughout the competition, and (3) a good running economy, i.e. a small value of C_r. Indeed, high correlations have been shown between VO_{2max} and running performance in groups of runners with fairly different abilities (Maughan and Leiper 1983; Sjodin and Svedenhag 1985). However, in groups of athletes of similar athletic capabilities, VO_{2max} becomes a less sensitive predictor of performance (Laursen and Rhodes 2001; Sjodin and Svedenhag 1985). As a matter of fact, also in the present study VO_{2max} did not differ significantly between the first five and the last five athletes (56.4 ± 4.9 vs. 51.8 ± 8.2 mlO_2 kg^{-1} min^{-1}, $P = 0.321$).

Several studies have shown that *F* is crucial for the performance in distance running (Billat et al. 2002; Maughan and Leiper 1983). During competition *F* is linked primarily to adaptations resulting from prolonged training (Holloszy and Coyle 1984), and the running velocity, at this intensity of VO_{2max}, is determined by the individual's ability to translate energy into performance (Daniels 1985), i.e. to the energy expenditure per unit of mass and distance (C_r).

Many studies have shown the major role of C_r in determining performances in middle and long-distance running (Conley and Krahenbuhl 1980; di Prampero 2003, 1986, 1993; Sjodin and Svedenhag 1985). It was also proposed that an increase of C_r throughout the event could explain the worst performance observed in some runners, whose other physiological characteristics determining performance (VO_{2max} and *F*) are equal to those of their more performance mates. Indeed, Brueckner et al. (1991) showed that C_r increases throughout a marathon, although to a relatively minor extent (0.142% per km of distance), so that the average increment of C_r at the end of the marathon was about 5%. However, these authors observed that the increase of C_r was widely different among runners who have similar characteristics in term of VO_{2max}, *F*, training level, age, etc., being essentially negligible at one extreme and twice the group average at the other.

In the present study, C_r increased significantly at the end of the second (+11.4%) and third (+7.2%) lap, being about 18% larger at the end of the lap 3 than before lap 1. This greater increase in C_r as compared to classical marathoners can be explained by the peculiarities of the race terrain, the characteristics of which stress greatly the physical capacities of athletes.

Although the role of each of the above factors (VO_{2max}, *F*, and C_r) may be difficult to identify in specific group of runners, di Prampero et al. (1986) have demonstrated that when taking all three of them into consideration, a clear-cut relationship between performance on the one side and VO_{2max}, *F*, and C_r on the other emerges. Indeed, these authors showed that, endurance speed (v_{end}) in long-distance running can be predicted, for any given runner, provided that his/her values of C_r, VO_{2max}, and *F* are known:

$$v_{end} = F \times VO_{2\,max} \times C_r^{-1} \quad (1)$$

where VO_{2max} and C_r are the values above resting and all variables must be expressed in compatible units. (If VO_{2max} is expressed in mlO_2 kg^{-1} min^{-1}, C_r in mlO_2 kg^{-1} m^{-1}, *F* being a dimensionless quantity, v_{end} will be turn out in m min^{-1}).

Equation 1, as written, does not take into account the increase of C_r that may occur during the competition. To consider also this possibility, we estimate the mean value of C_r throughout the race ($C_{r\text{-mean}}$) as follows:

$$\begin{aligned} C_{r-mean} = \{ & [(C_{rIo} + C_{rIf}) \times 0.5 \times d_I] \\ & + [(C_{rIIo} + C_{rIIf}) \times 0.5 \times d_{II}] \\ & + [(C_{rIIIo} + C_{rIIIf}) \times 0.5 \times d_{III}]\} \\ & \times (d_I + d_{II} + d_{III})^{-1} \end{aligned} \quad (2)$$

where the suffix I, II, and III refer to the first, second and third lap, o and f indicate the C_r value assessed immediately before and after the appropriate lap, the distance of which are indicate by d ($d_I = 22{,}000$ m; $d_{II} = 48{,}000$ m; $d_{III} = 20{,}000$ m). Therefore, applying Eq. 1) to the overall competition and taking into account the average value of C_r, as from Eq. 2), one obtains:

$$v_{end-mean} = F \times VO_{2\,max} \times C_{r-mean}^{-1} \quad (3)$$

This equation allowed us to estimate the overall performance time ($t_{overall}$):

$$t_{overall} = \text{distance overall} \times v_{end-mean}^{-1} = 90\text{ km} \times C_{r-mean} \times (F \times VO_{2\,max})^{-1} \quad (4)$$

In this study F was not determined as such. However as a first approximation, F can be assumed to be equal to the average HR (expressed as a percent of the individual HR_{max}) maintained throughout each lap. The data obtained in this study, the average of which are reported in Table 2, allowed us to obtains the individual values of $C_{r\text{-mean}}$ (2), F as from the time weighted average of the mean HR throughout each lap, and VO_{2max} assumed to be equal the value determined before the race (Table 1). The so obtained values were then entered in Eq. 4.

Their role in determining performance was then evaluated by stepwise multiple linear regression as described under "Statistical analysis" (see above), the results of which are reported in Table 4. This table shows that, in this group of runners, F has the largest role in determining performance ($R^2 = 0.69$) followed by $\dot{V}O_{2max}$ ($R^2 = 0.11$), $C_{r\text{-mean}}$ ($R^2 = 0.09$). When considering all three variables, the overall determination coefficient regression with the total race time (min) is described by the following equation:

$$\text{Total race time} = -2.64 \times F - 11.15 \times VO_{2\,max} + 12{,}586.83 \times C_{r-mean} - 1{,}033.98 \quad (5)$$

($R^2 = 0.87$, SE $= 27.33$ min, Fig. 1)

Thus Eq. 4, as written, explains 87% of the variance of performance. In addition, the measured and estimated total race times were not significantly different (9:25:50 ± 2:12:00 vs. 9:20:48 ± 2:21:36 h, $P = 0.878$).

The importance of a correct evaluation of the energy cost of running for estimating performance is further stressed by the following consideration. If, in Eq. 4 $C_{r\text{-mean}}$ is replaced by C_r, as measured before the race, the overall determination coefficient is reduced from 0.87 to 0.81, the individual role of C_r falling from $R^2 = 0.09$ to $R^2 = 0.04$.

It should be pointed out that the regression described by Eq. 5 and reported in Fig. 1, was obtained from the VO_{2max} values determined before lap 1. However, 5 days after the end of lap 3, VO_{2max}, although slightly lower than before lap 1, was not significantly different from it (Table 1). So we think that the choice of utilising one and the same VO_{2max} value, i.e. that determined before lap 1 does not introduce any systematic error in the estimate of the theoretical overall performance time, as from Eq. 4. More critical, in our opinion, is the estimation of F, i.e. of the fraction of VO_{2max} actually sustained throughout the competition. It should be pointed out in this connection that another possible way to estimate F from HR would have been to use HR reserve (rather than HR absolute) values, both expressed in percentage of the corresponding *maxima*.

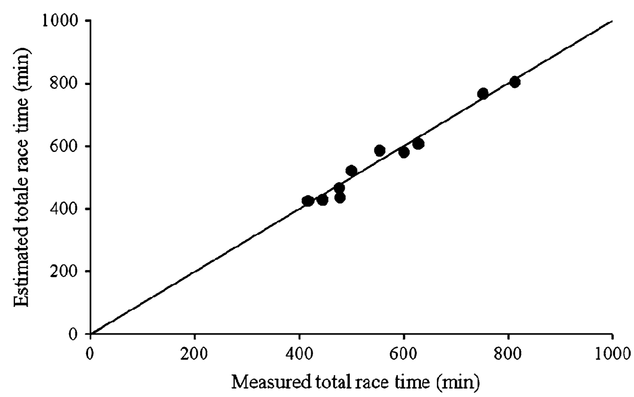

Fig. 1 Estimated total race time (min) as obtained from Eq. 4 is plotted for all athletes as a function of the measured total race time (min). Identity line is also shown (*thin line*)

Table 4 Stepwise multiple linear regression analysis for the prediction of total race time

Regression coefficients							
F (%)	$\dot{V}O_{2max}$ ($mlO_2\ kg^{-1}\ min^{-1}$)	$C_{r\text{-mean}}$ ($mlO_2\ kg^{-1}\ m^{-1}$)	C_r ($mlO_2\ kg^{-1}\ m^{-1}$)	Intercept	SE (min)	R^2_{adj}	P
−17.17 [0.69]				1,875.65	56.91	0.67	0.004
−15.22 [0.69]	−6.34 [0.11]			2,056.92	43.44	0.77	0.008
−2.64 [0.69]	−11.15 [0.11]	12,586.83 [0.09]		−1,033.98	27.33	0.87	0.016
−15.80 [0.62]	−8.05 [0.16]		−989.60 [0.04]	2,357.06	35.43	0.81	0.001

Coefficient of determination (R^2) for each factors in square brackets

F fractional utilisation of VO_{2max} throughout the race as determined from the mean HR, VO_{2max} maximal oxygen consumption measured before the race, $C_{r\text{-mean}}$ mean energy cost of running throughout the race as calculated by means of Eq. 2, C_r energy cost of running measured before, *SE* standard error, R^2_{adj}: adjusted coefficient of determination

However, because of the intrinsically larger variability of resting HR, we preferred to stick to absolute HRs, a fact that may lead to a small systematic error, without, however, greatly affecting our approach.

Finally, the actual value of C_r utilised in the calculation was obtained as described above (2), on the implicit assumption that C_r throughout any specific lap increase linearly with the distance covered.

In view of the above simplifying assumptions we would like to point out that Eq. 5 (see also Fig. 1) should be taken with a grain of salt. Nevertheless, we are confident that the above approach is theoretically sound, even if it goes without saying that, ideally, one would like to calculate the instantaneous speed from the corresponding values of the three relevant variables. By integrating over the entire duration of the race the so obtained instantaneous values, one could then calculate an overall mean speed with a better approximation than arrived at by means of Eq. 4. However, this scenario, appealing as it is, is far from our present possibilities.

In conclusion, the data presented above showed (1) that C_r increases significantly during the competition, and (2) that the athletes performance was a function of F, VO_{2max}, mean C_r throughout the race. These three variables explained 87% of the variance in the total race time.

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Conflict of interest The authors declare that they have no conflict of interest.

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